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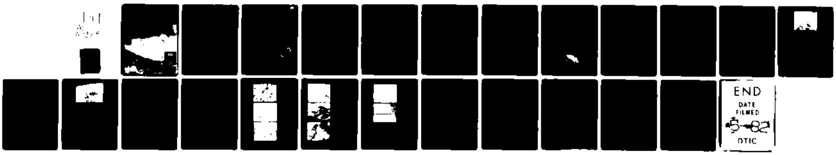

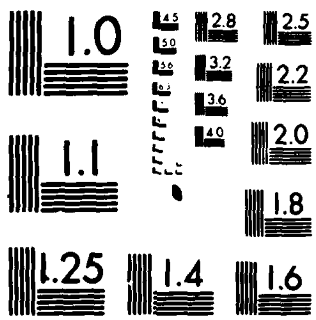


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## REPORT 81-27

## Sedimentological characteristics and classification of depositional processes and deposits in the glacial environment

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*Cover: Advancing margin of the Matanuska Glacier, Alaska, in 1980.*

CRREL Report 81-27

# *Sedimentological characteristics and classification of depositional processes and deposits in the glacial environment*


Daniel E. Lawson



December 1981





UNITED STATES ARMY CORPS OF ENGINEERS
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE, U.S.A.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER<br>CRREL Report 81-27 | 2. GOVT ACCESSION NO.<br>AD-A113261 | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle)<br>SEDIMENTOLOGICAL CHARACTERISTICS AND CLASSIFICATION OF DEPOSITIONAL PROCESSES AND DEPOSITS IN THE GLACIAL ENVIRONMENT | | 5. TYPE OF REPORT & PERIOD COVERED |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s)<br>Daniel E. Lawson | | 8. CONTRACT OR GRANT NUMBER(s) |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>U.S. Army Cold Regions Research and Engineering Laboratory<br>Hanover, New Hampshire 03755 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS |
| 11. CONTROLLING OFFICE NAME AND ADDRESS | | 12. REPORT DATE<br>December 1981 |
| | | 13. NUMBER OF PAGES<br>22 |
| 14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) | | 15. SECURITY CLASS. (of this report)<br>Unclassified |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Glacial deposits
Glaciers
Glaciology
Sedimentology
Sediment deposit classification

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Existing classifications for deposits in the glacial environment are inadequate and inconsistent. Deposits should be classified both descriptively and genetically; adequate descriptive classifications already exist. A major problem for previous genetic classifications has been that glacial deposition and the resulting deposits' properties were poorly understood.

On the basis of three criteria—sediment source, uniqueness to the glacial environment, and preservation of glacier-derived properties—deposits in the glacial environment result from either of two groups of processes: primary or secondary. Primary processes release the debris of the glacier directly and form deposits that may bear properties

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related to the glacier and its mechanics. Their deposits are classified genetically as till and are the only deposits indicative of glaciation. In contrast, secondary processes mobilize, rework, transport and resediment debris and deposits in the glacial environment. They develop new, *nonglacial* properties in their deposits, while destroying or substantially modifying clacier-derived properties. Interpretation of their properties may provide information on the depositional process and/or the local depositional environment. Secondary deposits are resedimented and therefore not till. They are classified genetically according to the depositional process just as they are in other sedimentary environments. This genetic classification differs from previous classifications in that not all diamictons deposited in the glacial environment are classified as till; it is based strictly on process-related criteria.

The origin of properties of glacial deposits in relation to the glacier's mechanics and environment must be recognized if the mechanisms and depositional processes of former glaciers are to be precisely understood.

## PREFACE

Dr. Daniel E. Lawson, Research Physical Scientist, Earth Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory, prepared this report as a member of the International Union for Quaternary Research (INQUA), Commission on the Genesis and Lithology of Quaternary Sediments. It was presented orally at the International Symposium on Processes of Glacier Erosion and Sedimentation in Geilo, Norway, on 27 August 1980. Dr. W. Hilton Johnson, Department of Geology, University of Illinois, and Timothy Kemmis, Iowa Geological Survey, critically reviewed the draft of this report and aided considerably in improving the final manuscript. Discussion with Dr. John Shaw, Dr. Geoffrey Boulton, Dr. David Croot and Dr. Ross Powell helped considerably in formulating ideas presented in this report. Written communications with members of the INQUA commission are gratefully acknowledged.

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# SEDIMENTOLOGICAL CHARACTERISTICS AND CLASSIFICATION OF DEPOSITIONAL PROCESSES AND DEPOSITS IN THE GLACIAL ENVIRONMENT

Daniel E. Lawson

## INTRODUCTION

Recent studies of sediments at active glaciers have shown earlier concepts of the depositional processes to be too simple and have raised important questions concerning the recognition and subsequent genetic classification of glacial deposits (Boulton 1972; Shaw 1977a, b, 1979; Lawson 1977, 1979a; Boulton and Eyles 1979; Eyles 1979, German et al. 1979). These studies show the complexity and importance of multiple erosional and depositional processes in the glacial sedimentary environment, and thus how composite stratigraphic sequences may develop during a single glacial cycle.

Of particular importance is the recognition that diamictons, traditionally interpreted as tills, may originate by a variety of different processes (e.g. Harrison 1957; Hartshorn 1958; Boulton 1970, 1975; Lawson 1975, 1979a; Shaw 1977a). These various processes form diamictons that may have significantly different sedimentological characteristics, although in outward appearance they are similar. These characteristics may originate directly from ice or may be derived through resedimentation adjacent to or beneath the glacier (Boulton 1978, Shaw 1979, Lawson 1979b). Diamictons of differing origins have been documented in a number of Quaternary and older stratigraphic sequences (e.g. Shaw 1971, 1979; Marcussen 1973; Edwards 1975; Gibbard 1980; Ojakangas and Matsch 1980).

In this paper, I will describe the sedimentological criteria that group the depositional processes and separate deposits into tills or nontills. These criteria will be illustrated in detail for two diamictons deposited at the margin of the Matanuska Glacier in Alaska (61°47'N, 147°45'W) (Fig. 1). I will also discuss the genetic classification of glacial sedimentary deposits and propose

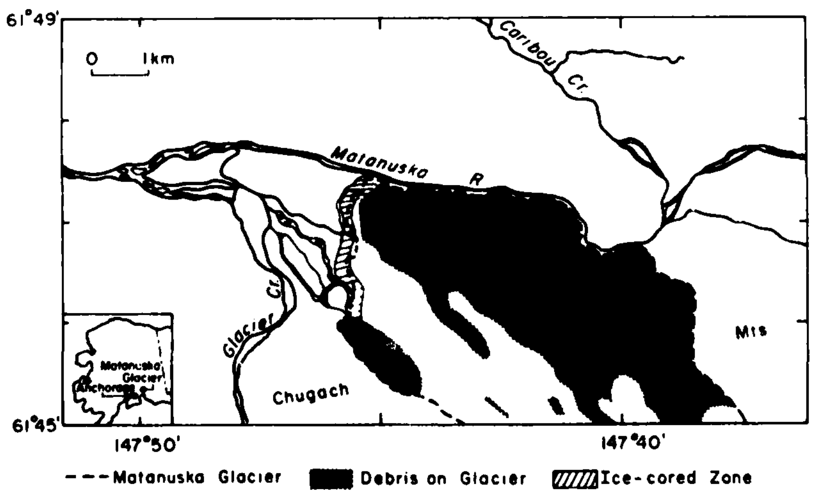



*Figure 1. Index map of Matanuska Glacier terminus with study area — the ice-cored zone — shown.*

a classification system that recognizes the fundamental differences among processes, sediment source, and location of deposition. These criteria and the general classification scheme will apply equally well to the processes and deposits of other active glaciers and to older glacial sediments as cited above.

## CRITERIA FOR PROCESS GROUPING

Three criteria separate all erosional and depositional processes of active glaciers into two groups called primary and secondary. Primary processes release and deposit sediment directly from glacier ice, whereas subsequent secondary processes cause resedimentation of glacial materials.

The sedimentological distinctions between primary and secondary processes are principally three: sediment source, uniqueness to the glacial environment, and ability to preserve glacial properties.

Primary processes derive their sediment only from debris in the glacier. Secondary processes mobilize, rework and resediment material previously deposited by primary or secondary processes and, less often, continue to transport and deposit debris immediately after release by a primary process.

Primary processes are unique to the glacial sedimentary environment, mainly because of their relationship to the glacier ice, whereas resedimentation processes are common to other sedimentary environments.

Primary processes can preserve the glacier's sedimentologic properties in their deposits. The debris and ice properties, and the depositional mechanism may imprint characteristics on glacial deposits that can be used to interpret a former glacier's entrainment, transport and depositional mechanisms, and the glacier's sediment source.

Conversely, transport and depositional mechanisms of the secondary processes develop the properties of their deposits. The properties of their source materials are modified and destroyed during mobilization and transport. The new properties that develop as a result of the resedimentation process are therefore *nonglacial.*

Because the ultimate source of sediment for both types of processes is the debris in the glacier, individual particles may retain properties, such as shape and surficial features, that are indicative of a glacial derivation (e.g., Boulton 1978, Lawson 1979a).

## DEPOSITIONAL PROCESSES

Primary processes at the Matanuska Glacier include melting of buried ice of the glacier's basal zone, ablation of active and stagnant basal zone ice that is exposed along the glacier's margin, and lodgement mechanisms operating during movement of the glacier over its bed (Lawson 1979a). A large amount of sediment is deposited today by melting of buried ice in the terminus region, with lodgement confined to areas upglacier from the terminus. Sediments released by ablation are usually not deposited but are transported and deposited by one or more of the secondary processes.

Subaerial and subsurface secondary processes are numerous. These processes include sediment gravity flow, spall (outward failure and collapse of steeply sloping sediments on melting, stagnant ice), sheet and rill flow of meltwater, thermal degradation and erosion, and gravitational settling in air and water. Fluvial, lacustrine and eolian processes are also secondary, operating in subglacial, englacial, supraglacial and proglacial parts of the environment.

Significant deposits are being formed by sediment flow, spall, meltwater sheet flow, and fluvial and lacustrine processes. The remaining processes are more important as erosional agents that expose buried, stagnant ice to ablation or that disaggregate and remobilize materials for resedimentation by other secondary processes.

## DEPOSIT GROUPS—TILLS AND NONTILLS

The sedimentologic distinctions between primary and secondary processes are useful in separating glacial deposits into two groups. I suggest that only sediments deposited by primary processes should be classified genetically as tills because only they are deposited directly from glacier ice and may possess properties derived from it. I define till as *sediment deposited directly by the glacier ice that has not subsequently undergone disaggregation and resedimentation.* I simply classify resedimented materials genetically by depositional process (e.g., sediment flow deposit). This latter use corresponds with the classification of deposits in other sedimentary environments.

These sedimentologic distinctions also determine how a glacial deposit's properties can be interpreted. In general, properties of secondary deposits can enhance understanding of the local depositional environment, while primary depos-

its may define properties and mechanisms of their glacier source. For example, some secondary processes are active only when certain environmental conditions exist; their deposits will therefore be valuable as indicators of these conditions.

Major differences therefore exist in the information contained in primary and secondary deposits which are critical to evaluating stratigraphic sequences. The following illustrate these differences.

The identification of the product of a primary process is *proof* of glaciation. The recognition of the deposit of a secondary process does not by itself indicate that glaciation took place, although the properties of individual particles in such deposits may indicate a glacial sediment source. The controversy over the glacial or nonglacial origins of diamictites of Precambrian and other ages (e.g., Schermerhorn 1974, Edwards 1975) is partly a failure to recognize that sediment flows and other related ice-marginal but "nonglacial" processes *are* in fact active in the glacial environment.

Glacier-derived properties of deposits in stratigraphic sequences must be separated from those of nonglacial origin before a sedimentological interpretation can be made. For instance, pebble orientations in glacial sediments may be indicative of ice flow conditions, or be unrelated to it and actually indicate local directions of paleoslope (Lawson 1979b). Indiscriminate measurement and analysis of pebble orientations in diamictons of the Matanuska Glacier would produce totally meaningless data. Similarly, other properties such as sedimentary structures, bedforms and other features can originate in multiple ways.

Compositional and textural variations in glacial sequences may originate from single or multiple depositional events. Boulton (1970, 1978) concluded that stratigraphic variations in the composition and texture of melt-out till and lodgement till deposited by Spitsbergen glaciers during a single depositional cycle probably represent similar variations in the basal debris of the glacier. But elsewhere, similar compositional and textural variations that represent multiple cycles of deposition by several different secondary processes have been observed along active ice margins (e.g. Shaw 1977a, Lawson 1979a).

Regardless of the origin, glacial deposits in stratigraphic sequences can only be identified genetically through detailed analysis of multiple properties (Goodchild 1875). At the Matanuska Glacier these properties include texture, internal structure, bed contacts, bedforms, deposit geometry, stratigraphic associations, deformational features and pebble fabric. Analysis of each of these properties is necessary because several processes (primary and secondary) may form deposits in which two or three of these properties are identical . Further, a single process can produce deposits with wide variations in these properties. The detailed natuie of the analyses does not differ from that required to interpret the origins of deposits of other sedimentary environments. A table showing these properties and their variability for selected deposits of the Matanuska Glacier is presented in one of my previous works (Lawson 1979a, p. 106–107).

## COMPARISON OF MELT-OUT AND SEDIMENT FLOW

As an illustration of the fundamental distinction between primary and secondary processes, and deposits, I will now compare melt-out with sediment flow. These processes were chosen because they form most of the deposits along the ice margin of the Matanuska Glacier today and they produce diamictons that would traditionally have been interpreted as till. Using the classification scheme described above, however, melt-out is a primary process that produces melt-out till, whereas sediment flow is a secondary process that produces sediment flow deposits. The properties of sediment flow deposits relate mainly to the sediment flow mechanisms of grain support, transport and deposition. A melt-out till's properties relate mainly to the properties of its ice and debris sources.

### Melt-out

Melt-out is the gradual in situ melting of the upper and lower surfaces of buried, debris-laden ice of a glacier's basal zone (Harrison 1957, Boulton 1970). The horizon of melting moves downward or upward into the ice mass and releases the debris under confining conditions that inhibit mixing and deformation (Fig. 2). Sediment released as the ice melts collapses, causing a readjustment of grain contacts and increased particle packing. Finer grained material migrates into the pore spaces between larger grains.

The melt-out process produces deposits that inherit most of their properties from the basal zone ice and debris. The extent of preservation or modification of these properties depends

**Tab 1. Comparison of properties of melt-out till and sediment flow deposits.**

| Deposit | Texture* Type 1) mean ($\phi$) 2) $\sigma$ ($\phi$) | Internal organization: General | Internal organization: structure | Internal organization: Pebble fabric | Surface forms | Contacts and basal surface features | Penecontemporaneous deformation | Geometry and maximum dimensions |
|---|---|---|---|---|---|---|---|---|
| Melt-out till | Gravel-sand-silt; silty sand; sandy silt. 1) 1 to 6 2) 1.8 to 3.5 | Clasts randomly dispersed in fine-grained matrix. | Massive; may preserve individual or sets of ice-debris strata as subparallel laminae and lenses. | Strong; unimodal parallel to local ice flow; low angle of dip. | Similar to ice surface; may be deformed or faulted. | Upper sharp, may be transitional; sub-ice probably sharp. | Possible internally and in overlying material during ice melt. | Sheet to discontinuous sheet; several km$^2$ in area, 1-6 m thick. |
| Sediment flow deposits (Increasing water content ↓) | Gravel-sand-silt, sandy silt, silty sand 1) 2 to 3 2) 3 to 4 | Clasts dispersed in fine-grained matrix. | Massive | Absent to very weak; vertical clasts. | Generally planar; also arcuate ridges, secondary rills and desiccation cracks. | Nonerosional conformable contacts; contacts sharp; load structures. | Possible subflow and marginal deformation during and after deposition. | Lobe: 50 x 20 m, 2.5 m thick |
| | Gravel-sand-silt, sandy silt, 1) 2 to 3 2) 3 to 4 | In plug zone, clasts dispersed in fine-grained matrix. | Massive; intraformational blocks common. | Absent to very weak; vertical clasts. | Arcuate ridges; flow lineations, marginal folds, mud volcanoes, braided and distributary rills. | Nonerosional, conformable contacts; contacts indistinct to sharp; load structures. | Possible subflow and marginal deformation during and after deposition. | Lobe: 30 x 20 m 1.5 m thick; sheet of coalesced deposits. |
| | | In shear zone, gravel zone at base, upper part may show decreased silt, clay and gravel content; overall, clasts in fine-grained matrix | Massive; deposit may appear layered where shear and plug zones are distinct in texture. | Absent to weak; bimodal or multimodal; vertical clasts. | | | | |
| | Gravelly sand to sandy silt 1) -2.5 to 2.5 2) 3.5 to 2 | Matrix to clast dominated; lack of fine-grained matrix possible; basal gravels. | Massive; intraformational blocks occasionally. | Moderate, multimodal to biomodal, parallel and transverse to flow direction. | Irregular to planar; singular rill development, mud volcanoes. | Nonerosional, comformable contacts; contacts indistinct to sharp. | Generally absent; possible subflow deformation on liquefied sediment. | Thin lobe or fan wedge: 30 x 65 m, 3.5 m thick, less often sheet of coalesced deposits. |
| | Sand, silty sand, sandy silt 1) >3.5 2) <2.5 | Matrix dominated except at base where granules possible. | Massive to graded (distribution, coarse-tail). | Absent | Smooth, planar; mud volcanoes possible. | Contacts conformable; indistinct. | Absent. | Thin sheet: 20 x 30 m, 0.3 m thick. Fills surface lows of irregular size and shape. |

*$\phi$—meangrain size, $\sigma$—standard deviation.


*Figure 2. Mostly massive melt-out till above its basal zone ice source. Dashed line x - x' marks till and ice contact. Arrow 1 locates a gravel-rich band in the till; arrow 2 locates a pebbly sand lens melting out of the basal ice. A gravel-rich layer is developing from ice-poor gravel strata in the basal ice. Dark layer is 30 to 60 cm wide.*

largely on the volume, distribution and texture of the debris in the ice. The overburden thickness, permeability of surrounding materials, and rates of melt-out influence the deposits' density and other physical properties (Boulton 1970).

At the Matanuska Glacier, the basal zone ice varies from 3 to 15 m thick and contains an average of 25% debris by volume (Lawson 1979a). This zone is stratified, with alternating debris-rich and debris-poor layers of ice. These layers vary in thickness from less than 1 mm to greater than 2 m and contain from less than 0.01% to greater than 80% debris by volume. Individual strata are actually composed of lenses and discontinuous to mostly continuous layers that contain individual grains and aggregates of sediment in suspension in ice, or of layers of sediment that contain only interstitial ice. Sedimentary structures, such as cross-stratification, may characterize the debris of the latter type of layers. Pebbles in the basal zone ice are preferentially oriented, usually with their longest axis aligned parallel to the local direction of ice flow (Lawson 1979b).

Observations of melt-out till and its basal ice source indicate that the following basal zone properties may be preserved (Table 1):

1. Pebbles generally remain preferentially oriented, with the scatter of individual particles about the calculated mean increasing slightly and the angle of dip decreasing substantially to near horizontal (Fig. 3) (Boulton 1971, Lawson 1979b).
2. Debris stratification may be preserved as lamina with gradational contacts in the till, usually with a near horizontal orientation.
3. Lenses and pods of texturally and structurally distinct materials with a subhorizontal orientation in the till develop by the melting of basal zone ice that has discontinuous layers and lenses of debris containing only interstitial ice (Fig. 4).
4. The bulk texture of the debris is preserved in the deposits.
5. Basal ice strata of low debris content and similarity of texture are not preserved but produce a structureless deposit.
6. The deposit geometry mirrors that of the ice source, although its dimensions are significantly reduced.

**Sediment flow**

Sediment flow is the downslope transport of sediment-water mixtures under the force of

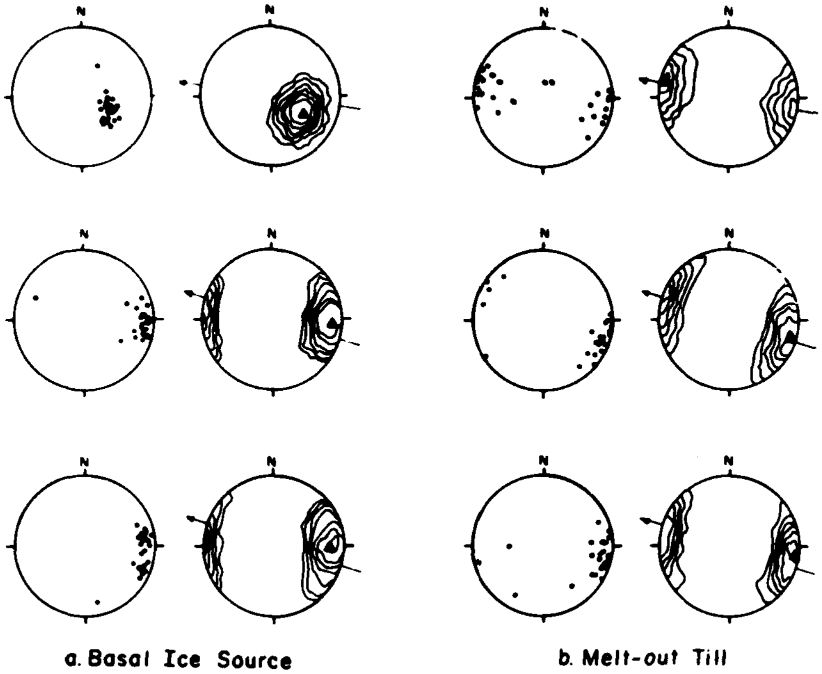



*Figure 3. Scatter plots and contoured Schmidt equal-area nets showing pebble orientations in the basal ice source (a) compared to melt-out till (b). Arrow shows local direction of ice flow. Triangle marks the mean axis orientation computed using the eigenvalue technique (Mark 1973). Contour interval 2ς according to method of Kamb (1959).*

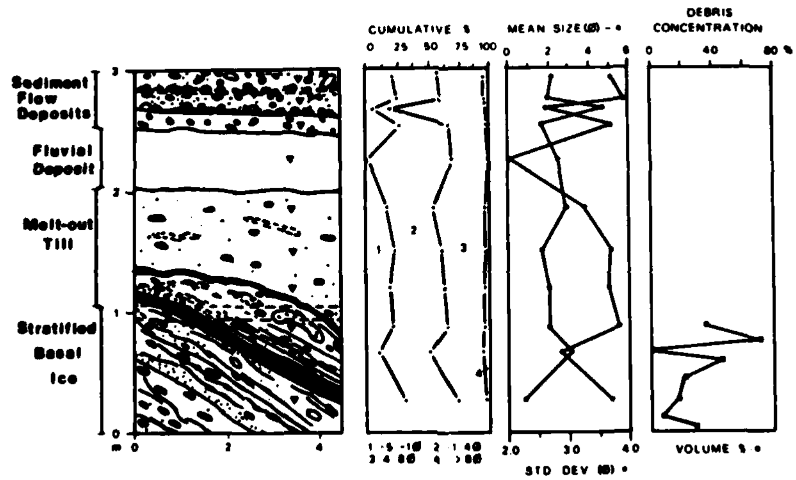



*Figure 4. Sketch of melt-out till overlying its ice source, with textural variations for the till and debris shown. Several debris strata were preserved during melt-out as lamina and lenses in the otherwise massive till. Debris strata in the ice dipped at about 25°, while in the till they are near horizontal.*

*Figure 5. Laterally retreating slope (about 8 m high) with ice core and near-vertical face. Sediments released during backwasting disaggregate, mix and accumulate at the slope's base. Failure and flow of this sediment follows. Some blocks of source material remain intact in the sediment flow at the slope's base.*

gravity. The source of most flows is the sediment and meltwater released during the lateral retreat of ice-cored near-vertical slopes (Fig. 5). Ablation of the ice core releases meltwater and debris, and undermines the overlying sediments. This sediment cover, which usually consists of melt-out till, sediment flow and other secondary deposits, then collapses. Material rolls, slides or falls to the slope's base where it accumulates on a slope of 1 to 7°. Here it is further mixed with the debris and meltwater. The continued influx of meltwater and thawing of the ice beneath the sediment pile develop excess pore pressures and generate seepage pressures. Both pressures reduce the resistance of these sediments to failure and flow (Lawson, in press). Flows also develop from sediment agitated during slumps, or from debris and meltwater that mix sufficiently as they are released from basal ice.

Each method of flow initiation destroys the sedimentologic properties of the source materials, except for those of individual grains. In some instances blocks of the source material may remain intact during the remolding process and are transported as clasts in the sediment flow.

The physical properties of sediment flow deposits are developed mainly by the flow's mechanism of grain support and transport (Table 1). Active sediment flows are characterized by multiple mechanisms of grain support and transport that vary in importance with the water content of the flow's matrix material during movement (Lawson, in press). Flows whose matrix material has a low water content move through shear in a thin zone at their base and support particles above this zone during transport by the strength of the matrix material. As the volume of water in the matrix increases, this shearing zone increases in thickness until the flow is in shear throughout (Fig. 6). Traction and saltation of coarse bedload material, localized fluidization and liquefaction, transient turbid mixing with flow over channel bed irregularities, and grain-to-grain interactions may also be active in such flows. Their importance may vary along the course of a flow. The flows with the highest water contents appear fully liquefied. Physical changes also occur as the water content increases; the density, thickness, areal extent and grain size of the flowing sediment decrease, while the flow's rate of movement, erosiveness and degree of channelization generally increase (Fig. 6).

The properties of flow deposits reflect these variations in flow mechanisms (Fig. 7). Individual deposits range in thickness from a few centimeters to about 2 m. The combination of pebble fabric, internal sedimentary structures, dimensions, geometry, bedforms and internal grain

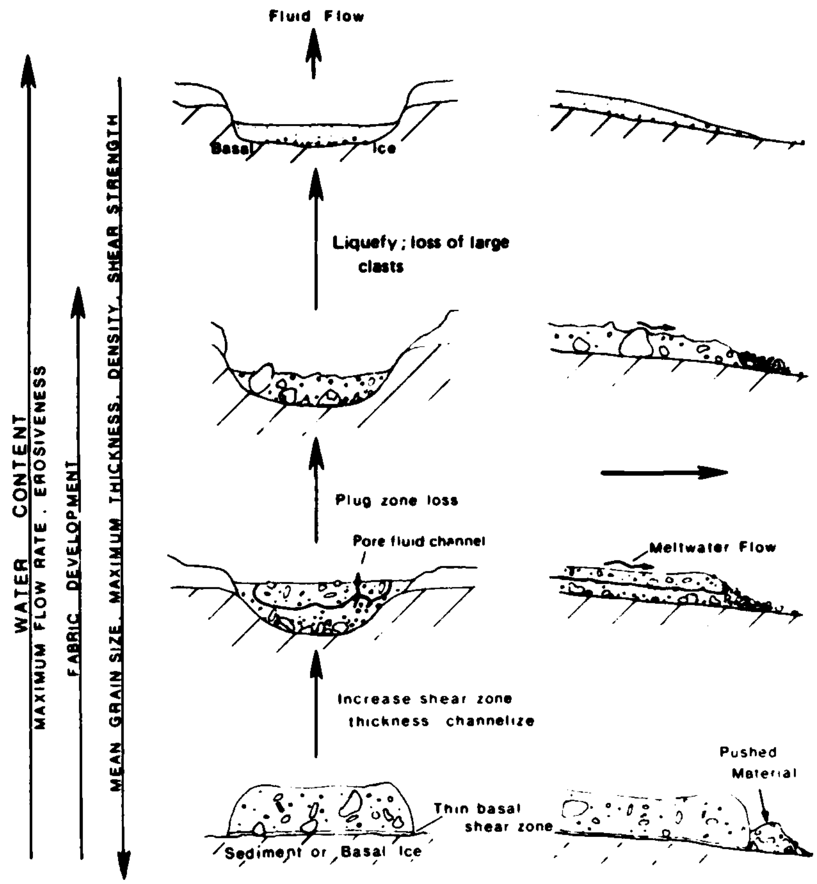



*Figure 6. Idealized cross sections, transverse and parallel to movement, of active sediment flows showing systematic changes in their form and other properties. Flows range from those possessing strength to those fully liquefied, with other mechanisms varying in importance. Channels are generally incised in glacier ice. Water content of the matrix material increases from bottom to top.*

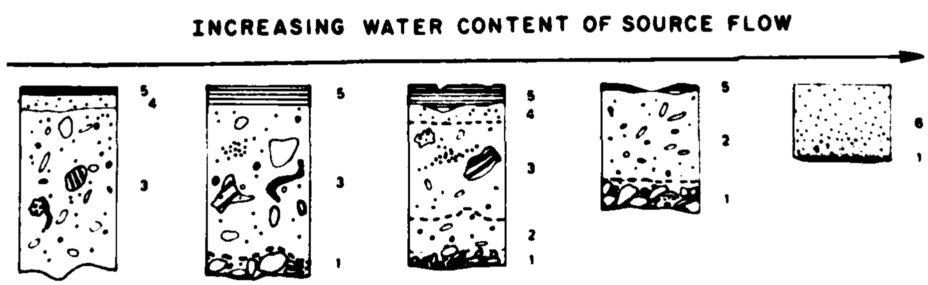



*Figure 7. Idealized internal organization of sediment flow deposits with variations in water content of the depositing flow. Six sedimentary units are recognized but any may be missing because of erosion or absence in source flow.*

***The characteristics of the units are as follows: Unit 1 — texturally heterogeneous with gravel zone of tractional origin, massive to normally graded, weak or absent pebble fabric. Unit 2 — massive and texturally heterogeneous but with a general absence of large grains, otherwise usually similar in texture to matrix of unit 3, weak pebble fabric. Unit 3 — mostly massive, but inclusions of texturally distinct or sometimes structured sediment may occur, pebble fabric absent, vertically oriented clasts common. Unit 4 — massive, fine-grained fraction (sand to clay) similar to matrix of unit 2, lacks coarse clasts. Unit 5 — horizontally laminated silts and sands deposited by meltwater. Unit 6 — massive or normal to coarse-tail grading, silty sand, fabric absent.***

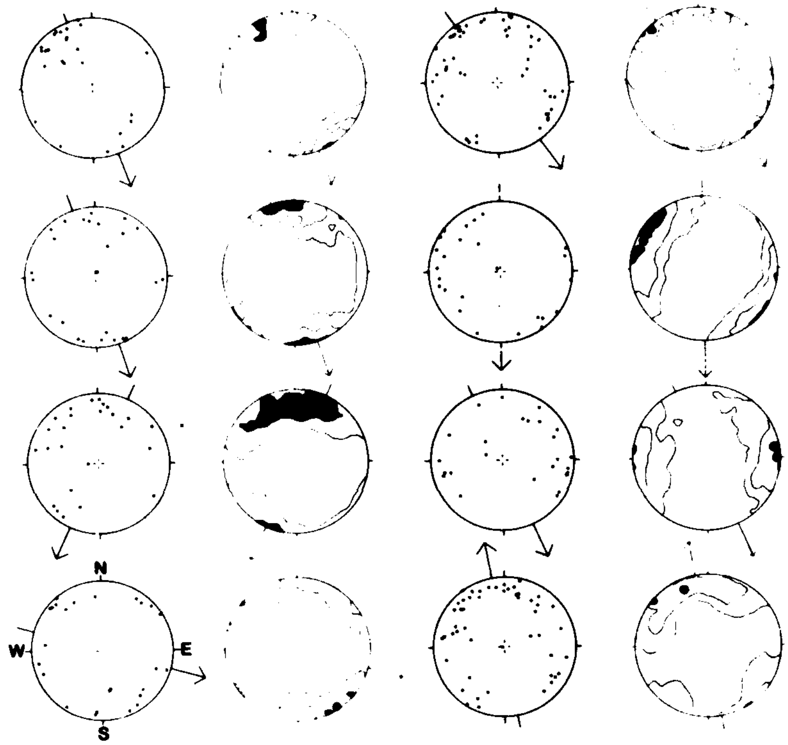
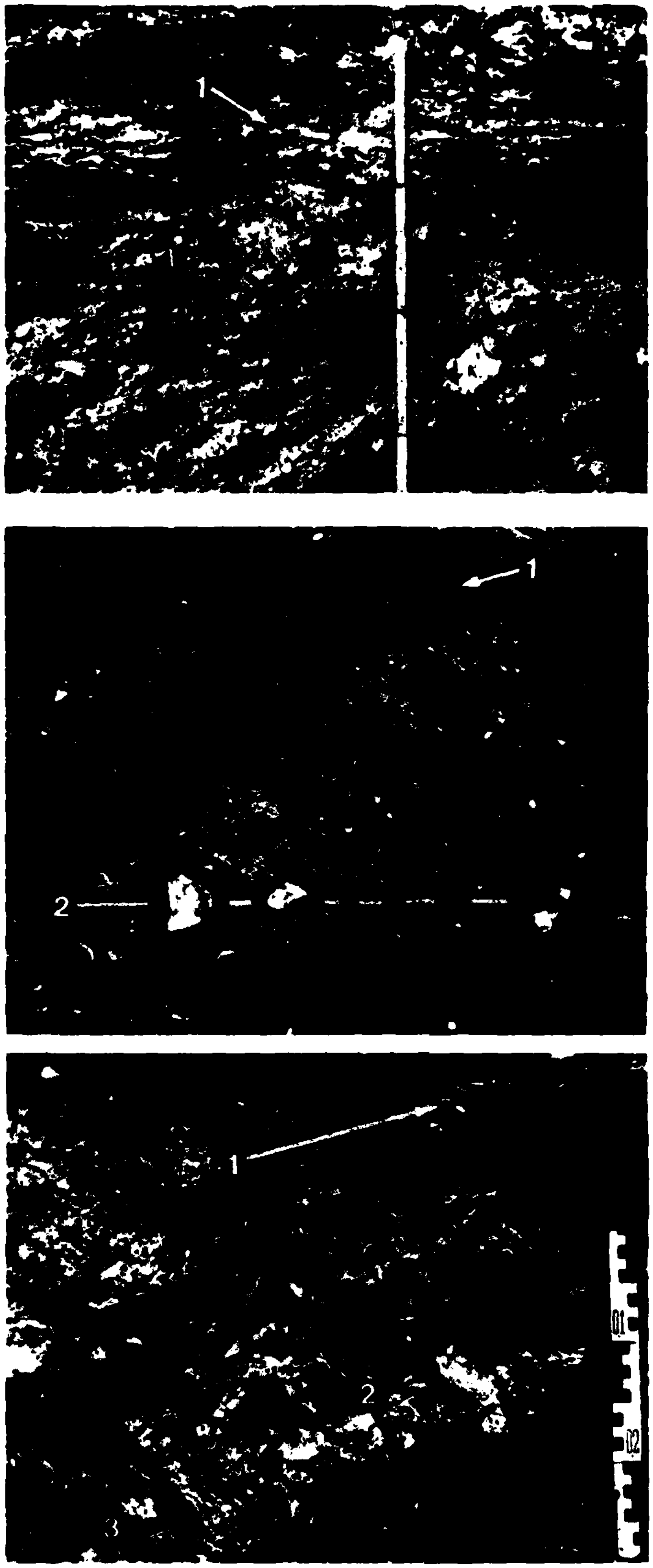



*Figure 8. Scatter plots and contoured equal-area nets showing pebble orientations in sediment flow deposits. Arrow shows direction of movement of source flow. Solid circle marks mean axis orientation (Mark 1973). Contour interval 2σ (Kamb 1959).*

size variations distinguish flow deposits from melt-out till and other deposits (Table 1). The following characteristics are typical of sediment flow deposits at the Matanuska Glacier:

1. Pebbles show a polymodal distribution of orientation, with individual observations widely dispersed about a poorly defined mean (Lawson 1979b) (Fig. 8). Particles show a poorly-defined, preferential orientation in shear zones of nonliquefied flows. Here, pebbles lie with their longest axis approximately parallel or transverse to the direction of the sediment flow's movement just prior to their deposition.
2. Internal variations in the coarser particle size fractions are often present in flow deposits and generally result from bedload transport or from settling of larger particles during solidification (Fig. 9).
3. Inverse, coarse-tail and normal gradings have been observed in liquefied flow deposits and in the tractional zone at the base of other flow deposits.
4. Flows impinging or overriding saturated sediments deform them and may be preserved in contact with these materials (Fig. 9).
5. Surface features that may be preserved are numerous and include flow lineations, meltwater rills, marginal folds, mud volcanoes, desiccation cracks and arcuate ridges (Fig. 10).
6. The extent of individual flow deposits is limited; the maximum dimensions observed for lobes and sheet deposits were 30 by 65 m.
7. Deposition in fans sometimes separates the more fluid flows into their grain-size components; fans are distinctive in form.
8. Most basal contacts are nonerosional. When deposition is on dry consolidated materials, it is sharp and recognizable. Soft material may deform by shear and develop load structures under the weight of the flow material (Fig. 9).




a. Mostly massive deposit, matrix dominated, without preferred pebble orientations. Top marked by stratified meltwater silts (1). Flow right to left, flow deposit is 48 cm thick.

b. A more fluid flow deposit with sharp basal contact defined by tractional gravels (2) and top marked by stratified meltwater silts and sands (1). Deposit possesses poorly defined preferred peble orientation that parallels flow. Movement direction left to right. Deposit 14 cm thick.

c. Multiple flow deposits with marginally deformed stratified silts (1), load structures (2) and conformable stratified gravelly sands. Intact blocks of source material (3) are present in some of the flow deposits. Scale in cm and dm.

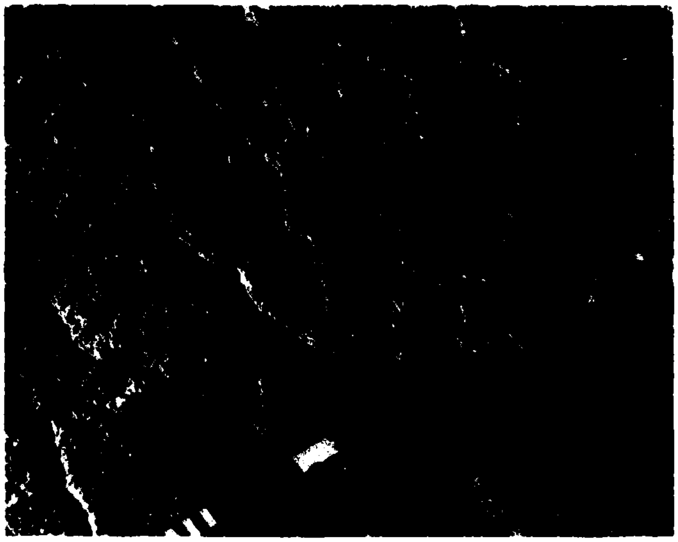
*Figure 9. Sediment flow deposits.*

*a. Partially reworked arcuate ridges on surface of consolidated flow deposit. Ridges develop by multiple influxes of material from the flow's source area into the body of the active flow. Scale at photo center is 2 m long. Movement right to left.*

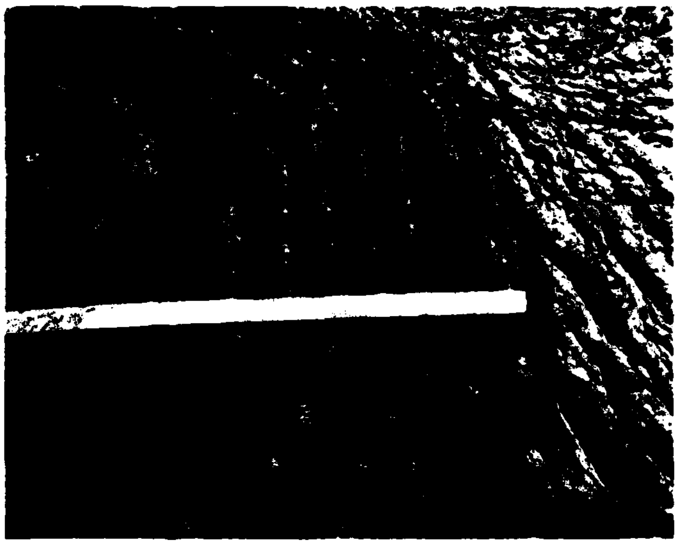
*b. Flow lineations developed during flow around boulder. Movement from center right to lower left. Scale in dm.*

*c. Mud volcanoes developed by pore fluid explusion through fluidization channels during consolidation of recent flow deposit. Approximately 34 cm of scale is showing.*

*Figure 10. Features of flow deposits' surface.*



d. Desiccation cracks in the surface of flow deposit. Approximately 70 cm of scale showing.



e. Marginal concentric folds developed in partially consolidated, fine-grained sediment flow deformed by compression at an active flow margin. Approximately 36 cm of scale showing.

Figure 10 (cont'd). Features of flow deposits' surface.

## CLASSIFICATION OF GLACIAL DEPOSITS

The current terminology for glacial deposits is inconsistent. Glacial geologists often use terms such as till, moraine and debris interchangeably to refer to the genesis or physical properties of glacial deposits (whether directly deposited from ice or resedimented), to material in transport in glacier ice, and to glacial landforms. I restrict the terms *debris* to sediment in transport in a glacier, *moraine* to a glacial landform, and *till* to glacial deposits of certain origins (as defined previously).

Rodgers (1950) emphasized the need for more than one system of classification for sedimentary rocks. At the minimum, both a descriptive and a genetic classification are needed to separate deposits of sedimentary environments.

The glacier and its environs should be considered as another sedimentary environment. While it has been classically overlooked by sedimentologists as being unimportant, the quantity of and widespread occurrence of glacially derived material deposited since Precambrian times requires recognition. The glacial environment is also extremely complex, involving interactions between ice, water and sediment under frozen and unfrozen conditions, with large diurnal and seasonal variations in climate and other parameters that can affect the mode of sedimentation and the stratigraphic sequences so developed.

**Table 2. Genetic classification of primary and secondary deposits based upon the relationship between process and location of deposition, and debris source and location.**

**a. Primary processes**

| *Debris (sediment in glacier transport)* | *Process of release/deposition* | *Position of deposition* | *Primary deposit classification* | *Preservation potential* |
|---|---|---|---|---|
| Supraglacial | Settlement by ice melt | Subaerial | Lowered till | Generally reworked |
| Englacial | Ablation | Subaerial | | Reworked |
| | Melt-out | Subsurface | Melt-out till | Generally reworked |
| | Ablation | Subaerial | | |
| Basal | Melt-out | Subsurface | Melt-out till (upper, lower) | Possible reworking |
| | Sublimation | Subsurface | Sublimation till | Possible reworking |
| | Tractional/frictional impairment or pressure melting | Subsurface (subglacial) | Tractional lodgement till (Clasts) to (Fines) Regelation lodgement till | Generally not reworked but may be glacio-tectonically deformed |

**b. Secondary processes**

| *Processes of transport/resedimentation* | *Secondary deposit classification* | *Preservation potential* |
|---|---|---|
| Sediment gravity flow | Sediment flow deposit | All secondary deposits may be reworked several times before final deposition. |
| Spall collapse | Slope colluvium | |
| Gravitational settling or falling through air or water | Ice-slope colluvium Waterlain colluvium | |
| Meltwater sheetflow | Sheetflow deposits | |
| Fluvial processes | Various glacio-fluvial deposits | |
| Lacustrine processes | Various glacio-lacustrine deposits | |
| Eolian processes | | |
| Thermal erosion and degradation | | |

As is standard practice with other sedimentary deposits, the first analysis should describe the material without any implied or stated origin. Descriptive classifications in sedimentology are usually based upon physical variations in properties such as grain size, composition, structure or other sedimentological features. Because such existing classifications are applicable to sedimentary deposits in general, a new classification for glacial deposits is not needed. Standard texts in sedimentology describe these classifications (e.g., Pettijohn 1957, Friedman and Sanders 1978, Blatt et al. 1980).

A genetic classification, however, should be

**Table 3. Example of facies association and facies for a possible composite depositional sequence at the ice margin of Matanuska Glacier.**

| *Location of process* | *Facies association* | *General material character* | *Genetic sedimentary facies* |
|---|---|---|---|
| Subaerial | Subaerial-resedimented | Unsorted | Sediment flow<br>Slope collapse<br>Ice colluvium |
| | | Sorted | Meltwater flow<br>Fluvial<br>Lacustrine |
| | Primary | Unsorted | Lowered |
| Subsurface | Primary | Unsorted | Melt-out<br>Lodgement |
| | Subglacial-resedimented | Unsorted | Sediment flow<br>Ice colluvium |
| | | Sorted | Meltwater flow<br>Fluvial<br>Lacustrine |

designed to account for the types of depositional processes at work in the environment and for the characteristics developed in their deposits that relate to and identify the origins of the deposits. Previous classifications of glacial deposits, including recent ones by Boulton (1972, 1976), ignored the differences between types of processes and the origins of deposit properties. The classification can also be based upon several elements of the depositional system; in the case of the glacial environment, the source of sediment, glacier-related properties and the position (relative to the surface and ice) of deposition are important in identifying deposits of different origin.

Table 2 illustrates a genetic classification based upon the debris' source and location, and on the primary or secondary processes and their relative position. The secondary processes that form diamictons and whose deposits traditionally would be called tills are included but are classified as they are in other sedimentary environments. Previous classifications considered all diamictons in the glacial environment, regardless of origin, as tills. Glaciofluvial and glaciolacustrine processes are included as groups, without the details of each type, for clarity.

The five main types of till delineated by studies of active glaciers are:

1. *Lodgement (tractional impairment)*—lodging of clasts one by one from overlying sliding or internally deforming ice. In classic lodgement, particles become stationary because frictional forces between the clast in traction and the bed become greater than the tractional force of the ice and they are deposited.
2. *Lodgement (regelation method)*—fine-grained debris may melt from actively moving basal ice that is at the pressure-melting point during regelation.
3. *Melt-out*—melt release of sediment from a debris-rich body of glacier ice as described earlier. Melt-out may be from glacier ice which is stagnant either as the result of general stagnation of the glacier or stagnation of discrete bodies of ice at the glacier sole.
4. *Sublimation*—as for melt-out, but with ice removal by sublimation.
5. *Lowered*—supraglacial debris which was never saturated with ice and is, therefore, considered to be deposited as soon as the underlying ice becomes stationary. It is lowered passively to its final resting place. Any sliding or transport by water after stagnation of the ice leads to reclassification of the material (Shaw, pers. comm.).

Genetic classification of glacial deposits requires full sedimentologic analysis of the depositional sequence and the individual units composing it. Currently this requires analyzing the entire assemblage of properties stated earlier.

Facies assemblages—repetitively occurring stratigraphic relationships of sediments formed under a given set of conditions—aid considerably in interpretation. Unfortunately research at active glaciers has yet to fully define them (Lawson 1977, Eyles 1979). Table 3 is an example of the general facies associations for the ice-marginal environment as they would occur in a composite vertical sequence along the western margin of Matanuska Glacier. Continuing studies at Matanuska Glacier are attempting to refine these and detail additional facies that develop here. Future studies at other glaciers should improve the applicability of facies for analyzing older glacial sediments.

## CONCLUSIONS

The fundamental criteria separating processes into two genetically related groups—sediment source, uniqueness to the glacial environment and preservation of glacier-derived properties—also separate *glacial deposits into groups that* can be interpreted readily in terms of glacial mechanisms, debris source and other environmental factors. Primary processes release the debris of the glacier directly and form deposits that may bear properties directly related to the glacier and its mechanics. I consider their deposits tills. In contrast, secondary processes mobilize, rework, transport and redeposit debris and deposits in the glacial environment. They develop new, *nonglacial* properties in these sediments. Interpretation of their properties may provide information on the depositional process and/or the local depositional environment. Secondary deposits are resedimented and are therefore not till, even though they are, in many instances, diamictons. They are classified according to the depositional process just as they are in other sedimentary environments.

It is imperative to recognize the fundamental distinctions between the origins of the properties of sediments deposited in the glacial environment. Otherwise, it is perilous to attempt to interpret glacial stratigraphic sequences in terms of their former depositional environment. Certain conditions in the glacial environment control the activity of individual processes as well as the sedimentation system as a whole. Factors such as climate, thermal regime, bed topography and composition, local meltwater availability, relief, weather and others affect erosion and deposition. Thus, once these conditions are well defined, analysis of the sediments may provide detailed glaciological as well as sedimentological data on past glaciers and their environment.

These distinctions between primary and secondary processes and the origins of deposit characteristics should be incorporated into any genetic classification scheme for glacial deposits. Previous classification schemes do not make such distinctions.

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Lawson, Daniel E.
Sedimentological characteristics and classification of depositional processes and deposits in the glacial environment / by Daniel E. Lawson. Hanover, N.H.: U.S. Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1981.
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